Effect of Soil Organic Carbon Distribution on Riparian Nitrate Attenuation During Stream Stage Fluctuations

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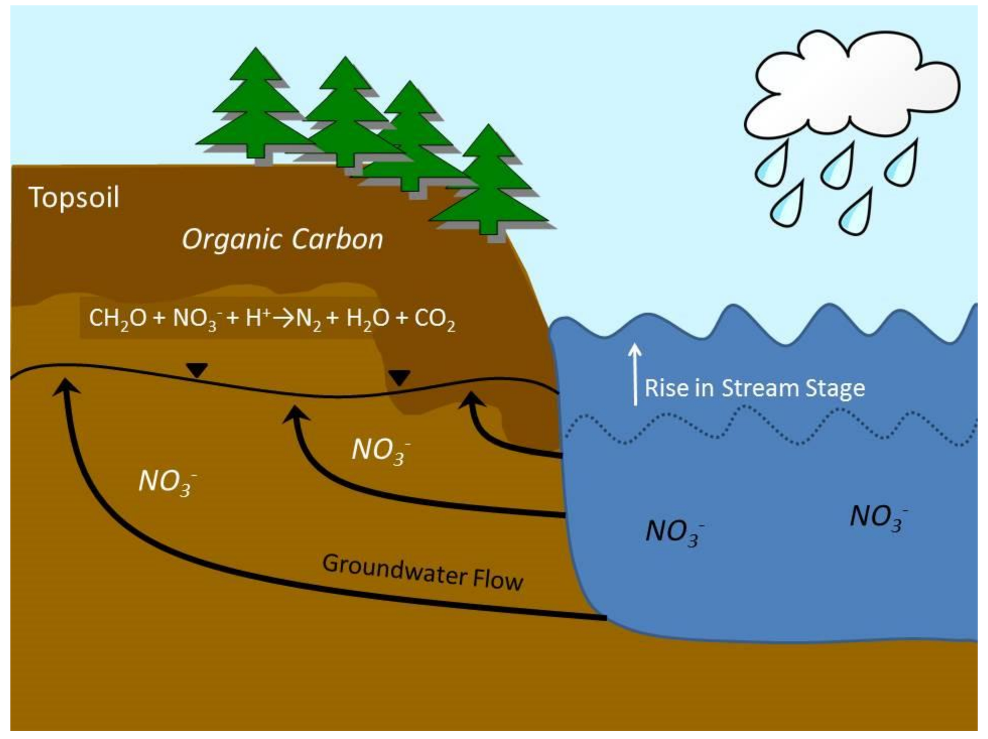
1. Introduction

Riparian zones occur at the interface between surface water and groundwater. These zones are critical locations for the occurrence of biogeochemical processes such as denitrification. Denitrification is an important natural process that removes nitrate pollution in streams and groundwater resulting from anthropogenic inputs. Stream stage fluctuations leading to increased bank storage have a strong effect on the removal of river-borne nitrate through facultative anaerobic microbial denitrification, referred to as "hot moments." Since the availability of oxygen and organic carbon are considered to exert the greatest control on denitrification rates, denitrification can be significant when the water table rises to reach the organic carbon-rich topsoils. Previous studies on denitrification during hot moments have focused on hydrologic controls as well as stream dissolved organic carbon input, but not the contribution of organic-carbon rich riparian soils.



Our goal is to quantify the effect of the vertical distribution of soil organic carbon on these denitrification hot moments during increased bank storage and provide a conceptual model to be used in further studies.

Figure 1. Schematic diagram of bank storage induced by stream stage rise and its effect on denitrification. As hyporheic exchange occurs, river-borne nitrate is brought to the organic matter (OM)-rich topsoil, which provides organic carbon (OC).

2. Study Site

The field data used in this study was collected from Boone Creek in Boone, NC, USA (Figure 2). Boone Creek is a third order perennial stream in the Upper South Fork of the New River watershed, located in the Blue Ridge Province of Western NC. The area of the Boone Creek sub-basin is 5.3 km^2 (Gu et al., 2015).

Figure 2. Boone Creek, NC on Feb. 16, 2018

Annual average rainfall is 1000-1400 mm/yr. Normal annual mean air temperature is 9.4°C, ranging from a daily average temperature of 20.3°C in July to -0.4°C in January (Gu et al., 2015). The surrounding area is mountainous, with an average slope of 27% (Gu et al., 2012). Boone Creek flows through an urbanized area, including the Town of Boone and the Appalachian State University campus, with a high degree of impervious surfaces nearby. The percentage of impervious area within a 12.2 m buffer of all streams in the drainage area is 32.2% (Gu et al., 2015).

3. Modeling Methodology

Model Domain & Boundary Conditions

A 3-D finite difference model, MODFLOW-NWT, was used to simulate groundwater flow. The model domain was 50 m wide, 5 m tall, and 2.5 m across (Figure 3). The grid consisted of 1 row, 78 columns, and 25 layers divided into 1,950 cells. The subsurface was approximated as homogenous and isotropic.

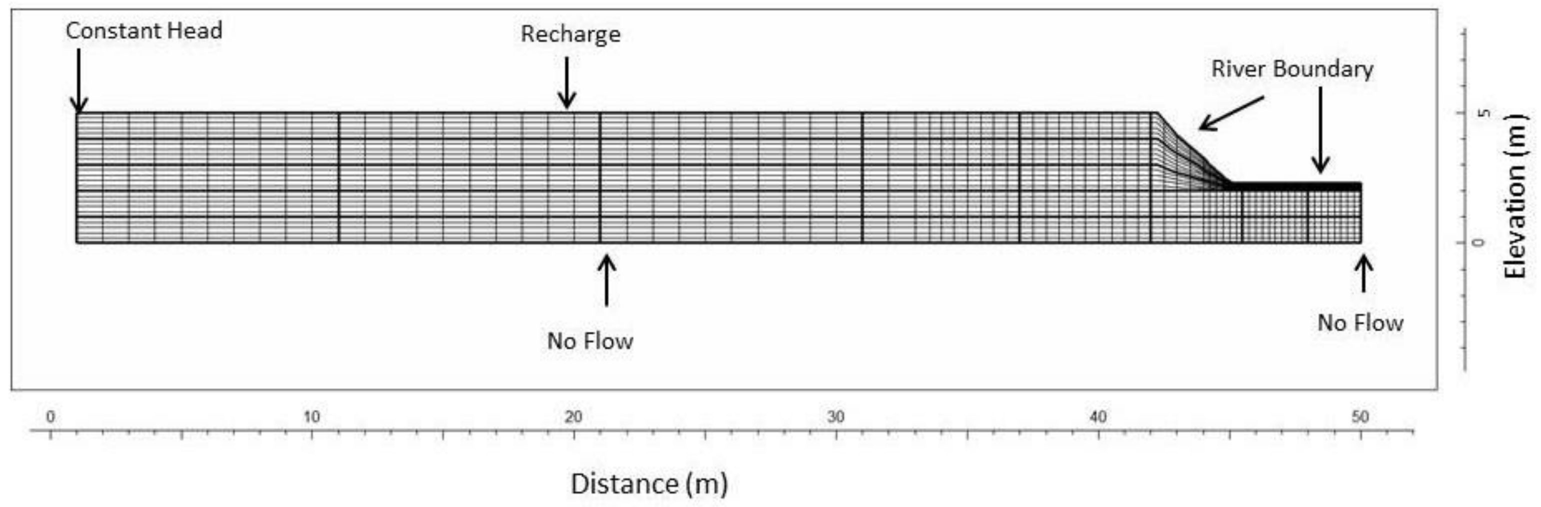


Figure 3. MODFLOW-NWT model domain and boundary conditions.

Table 1. Hydrologic parameters used in MODFLOW-NWT.

Parameter	Value
Hydraulic Conductivity, K	1.1×10^{-5} m/s
Recharge Rate	1.0×10^{-8} m/s
Hydrograph Peak	2.33 m
Hydrograph Duration	36 hr.
Specific Storage	1×10^{-5}
Specific Yield	0.2
Streambed Conductance	0.01 m/s
Porosity	0.25

Model boundary conditions are shown in Figure 3. The left (upslope) boundary was assigned a constant head of 3.5 m. The top of the model was assigned a constant recharge rate of 0.864 mm/d for the duration of the simulation. The bottom of the model and the right vertical boundary below the stream channel were assigned no flow boundary conditions. At the river boundary, the MODFLOW RIV package, a head-dependent flux (or "leaky") boundary condition, was used to simulate surface water-groundwater interaction (Reilly, 2001).

Hydrograph

We chose a 36-hour period between 2:15 am on October 8, 2017 and 2:15 pm on October 9, 2017 that included a stream stage rise from approximately 0.18 m (baseflow) to a peak stage of 2.33 m (Figure 4). Nine stress periods were utilized with smaller time steps during the hour prior to and the hour following peak stream stage.

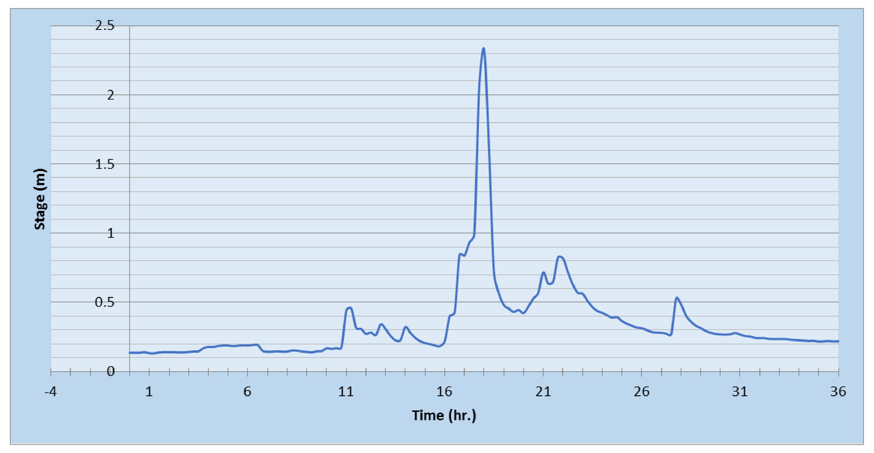


Figure 4. Boone Creek, NC hydrograph from storm event on October 8th-9th 2017

Solute Transport

Table 2. Chemical/physical parameters used in MT3D-USGS simulation.

Parameter	Value
Reaction Kinetics	1st Order
Longitudinal Dispersitivity	1 m
Total Organic Matter (%OM)	1-10%
Reaction Rate of Dissolved NO_3^-, k	$3.12 \times 10^{-5} - 3.06 \times 10^{-4}$ s^{-1}
Initial Concentration NO_3^- in Stream	10 mg/L
Initial Concentration NO_3^- in Aquifer	0 mg/L
Bulk Density	2 g/cm^3

Solute transport and the first-order decay reaction were modeled using the groundwater solute transport simulator MT3D-USGS. A sink-source mixing package was used at the river boundary to allow for solute to enter and exit the groundwater system, depending on the direction of flow. For the first simulation, a constant profile of 3% organic matter (OM) was assigned to a depth of 2 m and <1% OM below 2 m. For the second simulation, the OM content ranged from 10% at the surface to 1% at 5m depth. The total OM content was the same for each simulation.

Chemical Reaction

$$k = 0.011X + 0.0025$$

Where k is the denitrification rate constant (fraction of NO_3^- lost/hr.) and X is total soil C (mg/g).

The contribution of carbon (C) from OM-rich topsoils is kinetic-controlled. In this study, we simplified the denitrification process by assuming that the decrease in nitrate over time could be described by first-order kinetics. The relationship between total soil carbon (%OM) and the nitrate decay constant, k, was derived using this regression equation defined by Stanford et al. (1975).

4. Results

Bank Storage

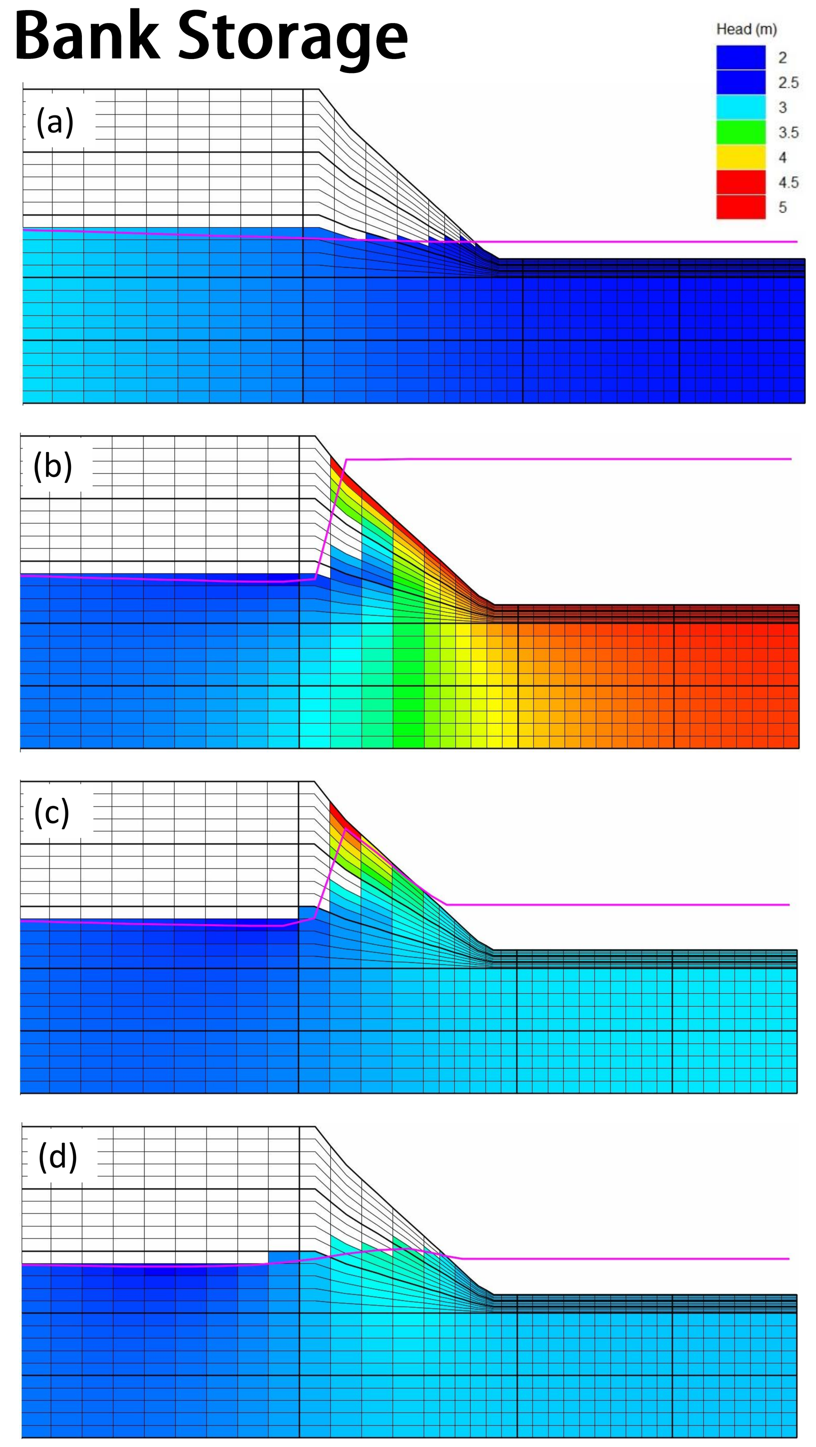


Figure 5. 2D Snapshots of head (a) prior to storm event, (b) 15 min. after peak, (c) 45 min. after peak, and (d) 5.5 hr. after peak. The bold pink lines represent the water table.

Solute Transport

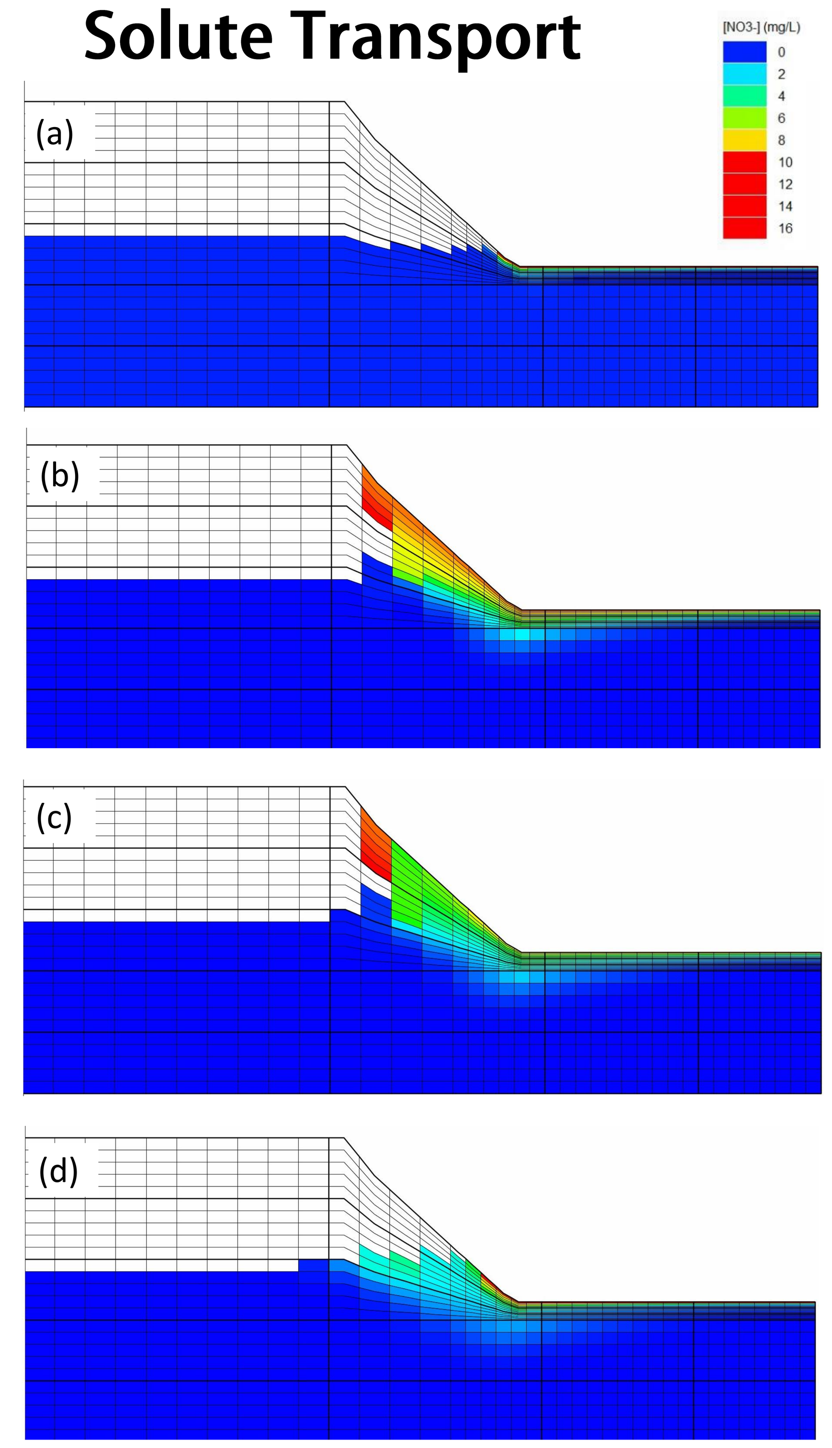


Figure 6. 2D Snapshots of [NO_3^-] simulated with an organic matter (OM) profile that decreased with depth: (a.) prior to storm event, (b) 15 min. after peak, (c) 45 min. after peak, and (d) 5.5 hr. after peak.

During the periods of highest stream stage, head in the subsurface near the stream increased significantly, indicating the flow of water back into the ground from the stream. Stream leakage is greatest at the stream bottom, but bank storage is also evident for most of the vertical extent of the stream bank. The nitrate is transported into the stream bank with the infiltrating stream water and is attenuated as it moves through the subsurface.

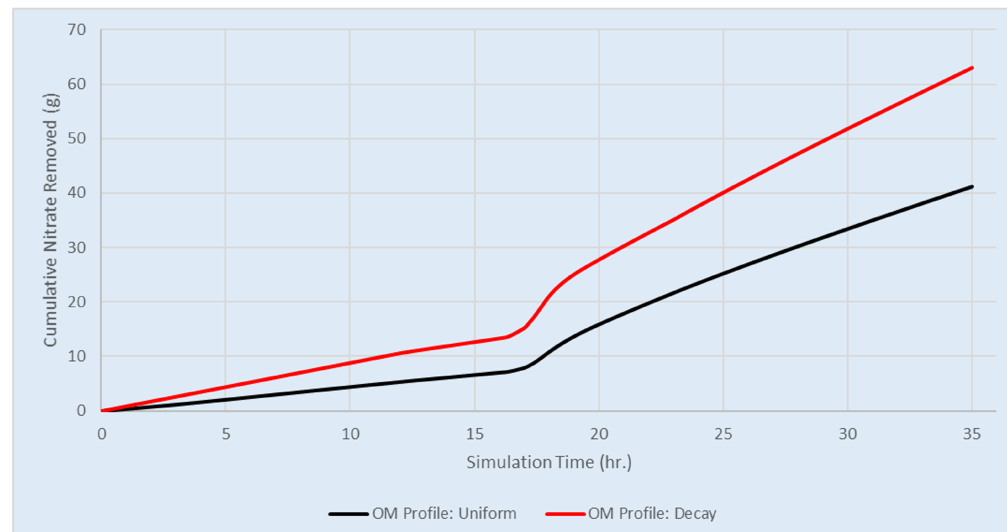


Figure 7. Plot of cumulative nitrate removal over time.

The simulated OM profile that decayed with depth exhibited greater nitrate removal throughout the simulation. The total nitrate removed via denitrification was 41.2 g and 63.1 g for the uniform and decaying OM profiles, respectively. This indicates that spatial distribution, in addition to total amount, of OM needs to be considered in quantifying riparian "hot moments."

References

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